Quantum codewords contradict local realism

David P. DiVincenzo

IBM Research Division, IBM T. J. Watson Research Center,
Yorktown Heights, New York, 10598

and

Asher Peres*

Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106

Abstract

Quantum codewords are highly entangled combinations of two-state systems. The standard assumptions of local realism lead to logical contradictions similar to those found by Bell, Kochen and Specker, Greenberger, Horne and Zeilinger, and Mermin. The new contradictions have some noteworthy features that did not appear in the older ones.

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*Permanent address: Department of Physics, Technion—Israel Institute of Technology, 32 000 Haifa, Israel

Quantum codewords are highly entangled combinations of two-state quantum sytems (qubits). They are structured in such a way that if one (or sometimes more) of the qubits is perturbed, there remains enough quantum information encoded in the remaining qubits for restoring the original codeword unambiguously [1, 2, 3, 4]. In this article, we shall investigate some properties of the 5-qubit codewords invented by Bennett, DiVincenzo, Smolin, and Wootters [5] (which are equivalent, up to a change of bases of the individual qubits, to the five-qubit codewords of Laflamme *et al.* [2]). The logical 0 is represented by the quantum state

$$\begin{aligned} |0_L\rangle = \tfrac{1}{4}\,[& -|00000\rangle \\ & -|11000\rangle - |01100\rangle - |00110\rangle - |00011\rangle - |10001\rangle \\ & +|10010\rangle + |10100\rangle + |01001\rangle + |01010\rangle + |00101\rangle \\ & +|11110\rangle + |11101\rangle + |11011\rangle + |10111\rangle + |01111\rangle], \end{aligned} \tag{1}$$

where, e.g., $|10010\rangle$ means $|1\rangle\otimes|0\rangle\otimes|0\rangle\otimes|1\rangle\otimes|0\rangle$, and $|0\rangle$ and $|1\rangle$ are any two orthogonal states of a physical qubit. The logical 1, denoted by $|1_L\rangle$, is obtained by exchanging all the $|0\rangle$ and $|1\rangle$ in $|0_L\rangle$. These two codewords have the useful property of being invariant under cyclic permutations of the physical qubits. This greatly simplifies the calculations below.

Let σ_x, σ_y, and σ_z be the standard Pauli spin matrices, and σ_u denote the unit matrix (the latter will also be denoted by the symbol 1, with no risk of error). It is convenient to introduce the notation

$$\sigma_{abcde} \equiv \sigma_{1a}\,\sigma_{2b}\,\sigma_{3c}\,\sigma_{4d}\,\sigma_{5e} \equiv \sigma_a\otimes\sigma_b\otimes\sigma_c\otimes\sigma_d\otimes\sigma_e, \tag{2}$$

where the indices $abcde$ may be any combination of u, x, y, and z. It is then readily verified that $|0_L\rangle$ and $|1_L\rangle$ are eigenvectors, with eigenvalue 1, of the 32 following operators: σ_{uuuuu}, $\pm\sigma_{zzzzz}$, and

$$\sigma_{xzuzx}, \quad \sigma_{yxuxy}, \quad \sigma_{zyuyz}, \quad \mp\sigma_{uxzxu}, \quad \mp\sigma_{yuzuy}, \quad \pm\sigma_{xyzyx}, \tag{3}$$

and their cyclic permutations. The upper and lower signs refer to $|0_L\rangle$ and $|1_L\rangle$, respectively (this convention will be followed throughout this article). These 32 operators (with either choice of sign) form an Abelian group; those whose sign does not change form an invariant subgroup. The existence of such a group associated with this type of quantum

error correction codes seems to be quite general. A group-theoretic framework for codes has been extensively developed by Gottesman [6] and by Calderbank *et al.* [7].

It is well known that, for any entangled state, it is possible to find operators whose correlations violate Bell's inequality [8, 9]. However the codeword (1) leads to a stronger type of violation, without inequalities [10, 11]. In this article, it will be shown that the codeword (1) and its associated operators (3) yield a rich crop of "quantum paradoxes." It appears that these paradoxical properties are inherent to all codewords of quantum error correcting codes. In particular, this is obviously true of the 9-qubit codewords of Shor [1], since the latter are built from triads of Mermin states [11].

It should be noted that the Mermin states,

$$[|000\rangle \pm |111\rangle]/\sqrt{2}, \tag{4}$$

can be used as codewords, for correcting a "bit error" ($0 \leftrightarrow 1$) in any one of the three qubits (but no other type of error). These states are eigenvectors, with eigenvalue $+1$, of an eight-element Abelian group:

$$\sigma_{uuu}, \quad \mp\sigma_{xyy}, \quad \mp\sigma_{yxy}, \quad \mp\sigma_{yyx}, \quad \pm\sigma_{xxx}, \quad \sigma_{zzu}, \quad \sigma_{zuz}, \quad \sigma_{uzz}. \tag{5}$$

To obtain quantum paradoxes for the five-qubit code (1), we note first that for each qubit, each one of σ_x, σ_y, and σ_z is an "element of reality," as defined by Einstein, Podolsky, and Rosen (EPR) [12]. This is so because the observable value of any one of these operators can be ascertained by measuring only *other* qubits, "without disturbing in any way" [12] the element of reality under consideration. For example, if we have prepared the five qubits in the state $|0_L\rangle$, the result of a measurement of σ_{1x} can be predicted with certainty by measuring σ_{2z} and σ_{3x}, because we know that $\sigma_{1x}\sigma_{2z}\sigma_{3x}|0_L\rangle = -|0_L\rangle$. Note that only the second and third qubits have to be measured in order to determine σ_{1x} (it is not necessary to measure the fourth and fifth ones). Other ways of determining σ_{1x} without interacting with the first qubit are to measure $\sigma_{4x}\sigma_{5z}$, or $\sigma_{3x}\sigma_{4y}\sigma_{5y}$, or $\sigma_{2x}\sigma_{3y}\sigma_{4z}\sigma_{5y}$, or $\sigma_{2x}\sigma_{3z}\sigma_{5z}$, or $\sigma_{2y}\sigma_{3y}\sigma_{4x}$, or $\sigma_{2y}\sigma_{3z}\sigma_{4y}\sigma_{5x}$, or $\sigma_{2z}\sigma_{4z}\sigma_{5x}$, as may be seen from the various operators in (3) and their cyclic permutations.

There are therefore eight different ways of determining σ_{1x} by means of measurements performed on the *other* qubits. However, these measurements cannot all be simultaneously

carried out, if each one of the qubits is tested separately, because they involve mutually incompatible, non-commuting one-particle operators (although the eight *products* of operators do commute, however, because their commutators always involve an even number of anticommutations). The notion of "element of reality" tacitly implies that these eight different determinations of σ_{1x} agree with each other. This may be intuitively obvious. However, classical intuition is a notoriously bad guide in the quantum world. There is no way of experimentally verifying that the eight methods agree. (At most, it is possible to verify that for some subsets of these operators, for example $\sigma_{2z}\sigma_{3x}$ and $\sigma_{4x}\sigma_{5z}$ can be tested simultaneously. There are only five such pairs among the eight operator products listed above.) The assumption that all eight ways of determining σ_{1x} necessarily agree is manifestly counterfactual. It is an example of the metaphysical hypothesis known as *local realism*. This hypothesis is incompatible with quantum mechanics, and leads to numerous contradictions, as will now be shown.

As one example, among many, consider the following six operators: $\pm\sigma_{1z}\sigma_{2z}\sigma_{3z}\sigma_{4z}\sigma_{5z}$, and $\mp\sigma_{1x}\sigma_{2z}\sigma_{3x}$ and cyclic permutations of the five qubits. If we measure the values of these six operators for one of the codewords, the result is 1, with certainty. Actually, the easiest way of measuring any one of these operators is to measure separately the physical qubits involved in it, and then to multiply the results. It is therefore tempting to assume that the values of the spin components of *individual* qubits also satisfy

$$v(\sigma_{1z})\,v(\sigma_{2z})\,v(\sigma_{3z})\,v(\sigma_{4z})\,v(\sigma_{5z}) = \pm 1, \tag{6}$$

and

$$v(\sigma_{1x})\,v(\sigma_{2z})\,v(\sigma_{3x}) = \mp 1, \tag{7}$$

and all cyclic permutations of Eq. (7). There are six equalities written above. The product of their right hand sides is -1. But on the left hand side, each symbol appears twice, and therefore the product of the left hand sides is $+1$. We have reached a contradiction, of the same type as in refs. [10] and [11]. It is graphically illustrated in Fig. 1.

It is also possible to obtain a Bell-Kochen-Specker [13, 14] type of contradiction, which does not refer to any particular quantum state, such as (1). Consider the following array of operators:

$$
\begin{array}{ccccccccccccc}
\sigma_{1z} & \sigma_{2z} & \sigma_{3z} & \sigma_{4z} & \sigma_{5z} & \quad & 1 & 1 & 1 & 1 & 1 & \quad & \sigma_{1z}\sigma_{2z}\sigma_{3z}\sigma_{4z}\sigma_{5z} \\
\sigma_{1z} & 1 & 1 & 1 & 1 & & 1 & \sigma_{2x} & 1 & 1 & \sigma_{5x} & & \sigma_{5x}\sigma_{1z}\sigma_{2x} \\
1 & \sigma_{2z} & 1 & 1 & 1 & & \sigma_{1x} & 1 & \sigma_{3x} & 1 & 1 & & \sigma_{1x}\sigma_{2z}\sigma_{3x} \\
1 & 1 & \sigma_{3z} & 1 & 1 & & 1 & \sigma_{2x} & 1 & \sigma_{4x} & 1 & & \sigma_{2x}\sigma_{3z}\sigma_{4x} \\
1 & 1 & 1 & \sigma_{4z} & 1 & & 1 & 1 & \sigma_{3x} & 1 & \sigma_{5x} & & \sigma_{3x}\sigma_{4z}\sigma_{5x} \\
1 & 1 & 1 & 1 & \sigma_{5z} & & \sigma_{1x} & 1 & 1 & \sigma_{4x} & 1 & & \sigma_{4x}\sigma_{5z}\sigma_{1x}
\end{array}
$$

All the operators in that array have eigenvalues ± 1, and therefore each one will yield one of these values, if measured in the standard way. Moreover, all the operators on each row commute, and their product is 1. Therefore, if all the operators on one of the rows are actually measured, the product of the resulting values is 1. Likewise, all the operators in each column commute, and their product is 1, *except those of the last column*, whose product is -1. It is therefore clearly impossible to associate to each operator a definite value, ± 1, that is unknown but would be revealed by a measurement of that operator, if such a measurement were actually performed. This is the multiplicative form of the Kochen-Specker contradiction [15, 16].

The original, additive form of the Kochen-Specker theorem can also be obtained from the above array. In its original formulation, that theorem asserted that there exist finite sets of projection operators, such that it is impossible to attribute to each one of the operators a bit value, "true" or "false," subject to the two following constraints:

KS1) two orthogonal projection operators cannot both be true, and

KS2) if a subset of orthogonal projection operators is complete (i.e., it has a sum equal to the unit operator), one of these projection operators is true.

In the physical interpretation of the Kochen-Specker theorem, orthogonal projectors correspond to mutually compatible quantum measurements, whose results are arbitrarily labelled 1 and 0, or "yes" and "no." The theorem asserts that there exist sets of n yes-no questions, such that none of the 2^n possible answers is compatible with the sum rules of quantum mechanics. This implies that there can be no subquantum physics, with hidden variables that would ascribe definite outcomes to the n yes-no tests (provided that the

hidden variables are not "contextual," namely that the answer to each question is unique, and does not depend on the choice of other questions being asked).

A set of Kochen-Specker projectors can now be obtained from the above array of operators as follows:

a) There is one complete set of eigenvectors that are common to all the operators in the first row: it is the "classical" basis $|00000\rangle$, $|00001\rangle$, ..., $|11111\rangle$. The 32 projectors on these vectors form a complete orthogonal set.

b) There is one complete set of eigenvectors that are common to all the operators in the last column of the array. These are the codewords $|0_L\rangle$ and $|1_L\rangle$, and the 15 mutations of each one of them, obtained by letting one of the Pauli matrices act on one of the physical qubits. The 32 projectors on these orthonormal vectors form another complete set. Each one is moreover orthogonal to 16 vectors of the "classical" basis, and vice-versa.

c) Each one of the five other rows generates eight mutually orthogonal 4-dimensional subspaces, that form a complete set. For example, the subspaces that correspond to the third row are the tensor products of the eigenvectors of σ_{1x}, σ_{2z}, σ_{3x}, and the complete subspaces of the two other qubits. The products of the three eigenvectors are

$$\tfrac{1}{2}\,(|0\rangle \pm |1\rangle) \otimes (|0\rangle \text{ or } |1\rangle) \otimes (|0\rangle \pm |1\rangle), \tag{8}$$

or

$$\begin{aligned} &\tfrac{1}{2}\,(|000\rangle + n\,|001\rangle + m\,|100\rangle + mn\,|101\rangle) \quad \text{for} \quad \sigma_{2z} > 0, \\ &\tfrac{1}{2}\,(|010\rangle + n\,|011\rangle + m\,|110\rangle + mn\,|111\rangle) \quad \text{for} \quad \sigma_{2z} < 0, \end{aligned} \tag{9}$$

where $m = \langle\sigma_{1x}\rangle$ and $n = \langle\sigma_{3x}\rangle$. The eight corresponding projection operators thus are

$$\tfrac{1}{4}(|000\rangle + n|001\rangle + m|100\rangle + mn|101\rangle)(\langle 000| + n\langle 001| + m\langle 100| + mn\langle 101|) \otimes 1 \otimes 1, \tag{10}$$

and

$$\tfrac{1}{4}(|010\rangle + n|011\rangle + m|110\rangle + mn|111\rangle)(\langle 010| + n\langle 011| + m\langle 110| + mn\langle 111|) \otimes 1 \otimes 1, \tag{11}$$

respectively. There are therefore 40 projectors of rank 4. They satisfy many mutual orthogonality relations, for example, any projector with $\langle\sigma_{1x}\rangle = 1$ in the third row of the array is orthogonal to any projector with $\langle\sigma_{1x}\rangle = -1$ in the sixth row.

Moreover, any rank 4 projector is orthogonal to many of the 64 projectors of rank 1, listed above. For example, all the projectors in (11), for any m and n, are orthogonal to all the "classical" vectors $|a0cde\rangle$. All the projectors in (11) with $m = n$ (so that $\langle\sigma_{1x}\sigma_{2z}\sigma_{3x}\rangle = -1$) are orthogonal to $|1_L\rangle$ and to all its mutations of type $\sigma_{4d}\sigma_{5e}|1_L\rangle$, and to some others. They are also orthogonal to the various mutations of $|0_L\rangle$, generated by σ_{1y}, σ_{1z}, σ_{2x}, σ_{2y}, σ_{3y}, σ_{3z}, or any odd number of the latter. (Not all these vectors are distinct, however.)

These numerous orthogonality relations have as a consequence that the constraints KS1 and KS2 cannot both be satisfied. The novel features in this Kochen-Specker contradiction is that projectors of rank 4 are used, and that the total number of projectors involved is remarkably low, when compared to the number of dimensions: $104/32 = 3.25$, while a similar construction in 4 dimensions requires 24 vectors [17], and in 8 dimensions, 40 vectors are involved [18].

We have likewise investigated the 7-qubit codewords of Steane [3]. They are simultaneous eigenvectors of 128 matrices of order 128, which are direct products of 3 to 7 Pauli matrices, and form an Abelian group. There are subsets of 10 group elements with properties similar to those listed in (6) and (7): each Pauli matrix corresponds to a local "element of reality," because the result of its measurement can be predicted with certainty by examining only *other* qubits. However, if it is assumed, in accordance with local realism, that each one of the local Pauli matrices is associated with a definite numerical value, ±1, an algebraic contradiction appears.

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References

[1] P. W. Shor, Phys. Rev. A **52**, 2493 (1995).

[2] R. Laflamme, C. Miquel, J. P. Paz, and W. H. Zurek, Phys. Rev. Lett. **77**, 198 (1996).

[3] A. M. Steane, Phys. Rev. Lett. **77**, 793 (1996); Proc. Roy. Soc. (London) A **452**, 2551 (1996).

[4] A. R. Calderbank and P. W. Shor, Phys. Rev. A **54**, 1098 (1996).

[5] C. H. Bennett, D. P. DiVincenzo, J. A. Smolin, and W. K. Wootters, Phys. Rev. A, **54**, 3824 (1996).

[6] D. Gottesman, Phys. Rev. A **54**, 1862 (1996).

[7] A. R. Calderbank, E. M. Rains, P. W. Shor, and N. J. A. Sloane, "Quantum Error Correction and Orthogonal Geometry," e-print quant-ph/9605005; "Quantum Error Correction via Codes over GF(4)," e-print quant-ph/9608006, submitted to IEEE Transactions on Information Theory.

[8] V. Capasso, D. Fortunato, and F. Selleri, Int. J. Theor. Phys. **7**, 319 (1973).

[9] N. Gisin and A. Peres, Physics Letters A **162**, 15 (1992).

[10] D. M. Greenberger, M. Horne, and A. Zeilinger, in *Bell's Theorem, Quantum Theory, and Conceptions of the Universe* ed. by M. Kafatos (Kluwer, Dordrecht, 1989) p. 69.

[11] N. D. Mermin, Physics Today **43** (no. 6), 9 (1990); Am. J. Phys. **58**, 731 (1990).

[12] A. Einstein, B. Podolsky, and N. Rosen, Phys. Rev. **47**, 777 (1935).

[13] J. S. Bell, Rev. Mod. Phys. **38**, 447 (1966).

[14] S. Kochen and E. P. Specker, J. Math. Mech. **17**, 59 (1967).

[15] A. Peres, *Quantum Theory: Concepts and Methods* (Kluwer, Dordrecht, 1993) p. 189.

[16] N. D. Mermin, Rev. Mod. Phys. **65**, 803 (1993).

[17] A. Peres, J. Phys. A **24**, L175 (1991).

[18] M. Kernaghan and A. Peres, Physics Letters A **198**, 1 (1995).

FIG. 1. Each side of the pentagon corresponds to three mutually compatible measurements. The product of the three results is guaranteed to have value ∓ 1, for $|0_L\rangle$ and $|1_L\rangle$, respectively. Moreover, the product of the five σ_z has to be ± 1. There is no consistent set of values for the twelve operators.

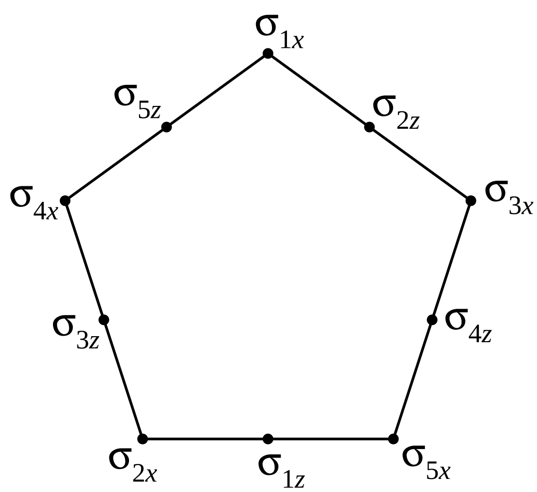

Figure 1. DiVincenzo and Peres

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